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**UTILITY PATENT APPLICATION TRANSMITTAL
(Small Entity)***(Only for new nonprovisional applications under 37 CFR 1.53(b))*Docket No.
55,112 (1850)Total Pages in this Submission
36**TO THE ASSISTANT COMMISSIONER FOR PATENTS**Box Patent Application
Washington, D.C. 20231

Transmitted herewith for filing under 35 U.S.C. 111(a) and 37 C.F.R. 1.53(b) is a new utility patent application for an invention entitled:

STILL METAL HUB FOR AN ENERGY STORAGE ROTOR

and invented by:

Norman C. BRACKETTIf a **CONTINUATION APPLICATION**, check appropriate box and supply the requisite information:☒ Continuation ☐ Divisional ☐ Continuation-in-part (CIP) of prior application No.: _____

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Enclosed are:

Application Elements

1. ☒ Filing fee as calculated and transmitted as described below
2. ☒ Specification having 16 pages and including the following:
 - a. ☒ Descriptive Title of the Invention
 - b. ☐ Cross References to Related Applications (*if applicable*)
 - c. ☐ Statement Regarding Federally-sponsored Research/Development (*if applicable*)
 - d. ☐ Reference to Microfiche Appendix (*if applicable*)
 - e. ☒ Background of the Invention
 - f. ☒ Brief Summary of the Invention
 - g. ☒ Brief Description of the Drawings (*if drawings filed*)
 - h. ☒ Detailed Description
 - i. ☒ Claim(s) as Classified Below
 - j. ☒ Abstract of the Disclosure

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Application Elements (Continued)

3. ☒ Drawing(s) *(when necessary as prescribed by 35 USC 113)*
a. ☒ Formal b. ☐ Informal Number of Sheets 3
4. ☒ Oath or Declaration
a. ☒ Newly executed *(original or copy)* ☐ Unexecuted
b. ☐ Copy from a prior application (37 CFR 1.63(d)) *(for continuation/divisional application only)*
c. ☒ With Power of Attorney ☐ Without Power of Attorney
d. ☐ DELETION OF INVENTOR(S)
Signed statement attached deleting inventor(s) named in the prior application,
see 37 C.F.R. 1.63(d)(2) and 1.33(b).
5. ☐ Incorporation By Reference *(usable if Box 4b is checked)*
The entire disclosure of the prior application, from which a copy of the oath or declaration is supplied under
Box 4b, is considered as being part of the disclosure of the accompanying application and is hereby
incorporated by reference therein.
6. ☐ Computer Program in Microfiche
7. ☐ Genetic Sequence Submission *(if applicable, all must be included)*
a. ☐ Paper Copy
b. ☐ Computer Readable Copy
c. ☐ Statement Verifying Identical Paper and Computer Readable Copy

Accompanying Application Parts

8. ☒ Assignment Papers *(cover sheet & documents)*
9. ☐ 37 CFR 3.73(b) Statement *(when there is an assignee)*
10. ☐ English Translation Document *(if applicable)*
11. ☐ Information Disclosure Statement/PTO-1449 ☐ Copies of IDS Citations
12. ☐ Preliminary Amendment
13. ☒ Acknowledgment postcard
14. ☒ Certificate of Mailing
☐ First Class ☒ Express Mail *(Specify Label No.):* EL440514296US

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Accompanying Application Parts (Continued)

15. ☐ Certified Copy of Priority Document(s) *(if foreign priority is claimed)*
16. ☒ Small Entity Statement(s) - Specify Number of Statements Submitted: 1
17. ☐ Additional Enclosures *(please identify below):*

Request That Application Not Be Published Pursuant To 35 U.S.C. 122(b)(2)

18. ☐ Pursuant to 35 U.S.C. 122(b)(2), Applicant hereby requests that this patent application not be published pursuant to 35 U.S.C. 122(b)(1). Applicant hereby certifies that the invention disclosed in this application has not and will not be the subject of an application filed in another country, or under a multilateral international agreement, that requires publication of applications 18 months after filing of the application.

Warning

An applicant who makes a request not to publish, but who subsequently files in a foreign country or under a multilateral international agreement specified in 35 U.S.C. 122(b)(2)(B)(i), must notify the Director of such filing not later than 45 days after the date of the filing of such foreign or international application. A failure of the applicant to provide such notice within the prescribed period shall result in the application being regarded as abandoned, unless it is shown to the satisfaction of the Director that the delay in submitting the notice was unintentional.

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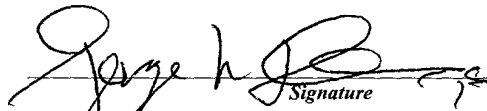
Fee Calculation and Transmittal

CLAIMS AS FILED

| For | #Filed | #Allowed | #Extra | Rate | Fee |
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| Total Claims | 13 | - 20 = | 0 | x \$9.00 | \$0.00 |
| Indep. Claims | 1 | - 3 = | 0 | x \$40.00 | \$0.00 |
| Multiple Dependent Claims (check if applicable) <input type="checkbox"/> | | | | | \$0.00 |
| BASIC FEE | | | | | \$355.00 |
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- ☒ A check in the amount of **\$355.00** to cover the filing fee is enclosed.
- ☒ The Commissioner is hereby authorized to charge and credit Deposit Account No. **04-1105** as described below. A duplicate copy of this sheet is enclosed.
- ☐ Charge the amount of _____ as filing fee.
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- ☐ Charge the issue fee set in 37 C.F.R. 1.18 at the mailing of the Notice of Allowance, pursuant to 37 C.F.R. 1.311(b).

Dated: November 3, 2000


Signature

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CC:

Applicant(s): Norman BRACKETT

Application No.: Unassigned

Filed: Herewith

For: STIFF METAL HUB FOR AN ENERGY STORAGE ROTOR

VERIFIED STATEMENT (DECLARATION) CLAIMING SMALL ENTITY
STATUS (C.F.R. 1.9(F) AND 1.27) - SMALL BUSINESS CONCERN

I hereby declare that I am

- ☐ the owner of the small business concern identified below:
☒ an official of the small business concern empowered to act of behalf of the concern identified below:

NAME OF CONCERN: BEACON POWER CORP.

ADDRESS: 6D GILL STREET, WOBURN, MASSACHUSETTS 01801

I hereby declare that the above identified small business concern qualifies as a small business concern, as defined in 13 CFR 121.3-18, and reproduced in 37 CFR 1.9(d), for purposes of paying reduced fees under Sections 41(a) and (b) of Title 35, United States Code, in that the number of employees of the concern, including those of its affiliates, does not exceed 500 persons. For purposes of this statement, (1) the number of employees of the business concern is the average over the previous fiscal year of the concern of the persons employed on a full-time, part-time or temporary basis during each of the pay periods of the fiscal year, and (2) concern are affiliates of each other when either, directly or indirectly, one concern controls or has the power to control the other, or a third-party or parties controls or has the power to control both.

I hereby declare that rights under contract or law have been conveyed to, and remain with, the small business concern identified above, with regard to the invention entitled

STIFF METAL HUB FOR AN ENERGY STORAGE ROTOR

By inventor(s): Norman BRACKETT

Described in

- ☒ the specification filed herewith.
☐ the application no. _____ filed _____
☐ the patent no. _____, issued _____.

If the rights held by the above identified small business concern are not exclusive, each individual, concern or organization having rights in the invention is listed below* and no rights to the invention are held by any person, other than the inventor, who would not qualify as an independent inventor under 37 CFR 1.9 (c), if that person made the invention, or by any concern which would not qualify as a small business concern under 37 CFR 1.9 (d) or a nonprofit organization under 37 CFR 1.9 (e).

NAME _____
ADDRESS _____

☐ Individual ☒ Small Business concern

I acknowledge the duty to file, in this application or patent, notification of any change in status resulting in loss of entitlement to small entity status prior to paying, or at the time of paying, the earliest of the issue fee or any maintenance fee due after the date on which status as a small entity is no longer appropriate (37CFR 1.28(b)). I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further, that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application, any patent issuing thereon, or any patent to which this verified statement is directed.

NAME OF PERSON SIGNING Matthew Lazarewicz

TITLE OF PERSON Vice President of Engineering

ADDRESS OF PERSON SIGNING: 6D GILL STREET, WOBURN, MA 01801

SIGNATURE: 

DATE 10/31/00

STIFF METAL HUB FOR AN ENERGY STORAGE ROTOR

FIELD OF THE INVENTION

The present invention relates to a metal hub for an energy storage rotor. More precisely, the invention relates to a stiff metal hub for a flywheel that maintains tight interference fit with a radially-deflecting composite rim during high-speed operation by deflecting at the hub outer rim, which minimizes vibrations, and produces a critical velocity substantially higher than the design operating velocity.

DESCRIPTION OF THE RELATED ART

Energy storage rotors, or flywheels, which internally produce and store kinetic energy, have been available as an alternative to batteries and other means of storing energy for about 30 years. Initially, flywheel assemblies were made of metal, e.g., high strength steel. However, flywheels made from composite materials provide superior energy storage capability to steel flywheels as the high-strength, lighter-weight composite flywheels can be rotated at greater speed. Recognizing that energy storage is proportional to the flywheel mass and the square of rotational velocity, substantially increasing rotational velocity and marginally decreasing mass by replacing steel with a composite material provides greater energy storage. Technological advances, thus, have made flywheel assemblies lighter in weight and capable of operating at higher operating speeds by using fiber composite materials, e.g., fiberglass or carbon fibers wound with a resin binder (carbon-carbon composite), in flywheel assemblies. The low density, high strength composite materials are ideally suited for flywheel assemblies, especially flywheel rings, which play a dominant role in overall flywheel energy storage.

High rotational operating velocities, however, produce extremely high centrifugal forces, which produce high radial and hoop stresses in the outermost composite rim. High stresses in the composite rim cause the rim to

“grow” radially, i.e., to deform outwardly in a radial direction. The flywheel hub, which holds the composite rim on a rotary shaft, generally by tight interference fit, is traditionally made of a high strength, lightweight metal alloy or a composite material. Metal alloy hubs provide strength and stiffness to the flywheel assembly. However, metal hubs often do not experience radial growth commensurate with, or of the same magnitude as, the deforming composite rim. Consequently, the composite rim separates from the hub, which produces potentially deleterious vibrations. Hubs made from composite materials as a rule are more flexible, which substantially minimizes separation between the hub and the composite rim. However, composite hubs as a rule are not sufficiently stiff to produce a critical velocity that exceeds design operating speeds.

As a composite rim separates from a hub, holidays, or gaps, in the tight interference fit appear between the hub and the composite rim, causing undesirable and potentially deleterious vibrations. Such vibrations are detrimental to the operation of the flywheel assembly. Moreover, if they occur at the natural, or resonant, frequency of the flywheel assembly and/or the component parts of the flywheel assembly, these vibrations could seriously damage or altogether destroy the flywheel assembly. Thus, those of ordinary skill in the pertinent art have focused a great deal of attention on means of solving the compatibility problem associated with flywheel assemblies having lightweight, high strength composite rims.

Medlicott (USP 4,821,599) discloses an energy storage flywheel with at least one (but preferably two or more) “substantially circular dished member” having an elastic modulus less than the elastic modulus of the composite ring. As the Medlicott flywheel rotates at higher velocities, the dished member deforms elastically causing the periphery of the dished member to move outwardly radially, maintaining contact with the less elastic composite ring, which also is expanding radially. However, with dished member hubs, having a lower modulus than the composite ring, the flywheel is less rigid and, consequently, more prone to vibrate than a system with a more rigid hub. Moreover, design operating speeds typically are greater than critical velocities,

requiring the flywheel system during operation to transition through the critical frequency.

Flanagan et al. (USP 4,860,611) also discloses an energy storage rotor with a flexible rim hub. The Flanagan invention provides an expanding aluminum hub design on which a composite ring is shrunk-fit. The Flanagan hub includes a plurality of spokes that are joined at the periphery by a continuous rim. The sections of the rim between adjacent spokes are purposely made thinner, thereby allowing the rim sections between adjacent spokes to flex outwardly to maintain interference fit with the composite ring. Flanagan et al. discloses that tight interference fit at lower operating frequencies and rim flexibility at higher operating frequencies substantially minimize vibrations and separation. Indeed, Flanagan expresses that critical frequency, i.e., resonance, does not occur because the rotor reaches its design operating speed, which is well above critical velocity, rapidly “so that the rotor does not pass through potentially destructive critical frequency.” However, in fact, the Flanagan flywheel system requires that the rotor pass through the critical frequency, subjecting the rotor to potentially deleterious vibrations.

Bitterly et al. (USP 5,124,605) discloses a flywheel with a “self-restoring bearing system” that comprises a hub that is joined to a composite ring by a plurality of tube assemblies. The tube assemblies, which are attached to the hub and the composite ring, allow differential radial expansion in the hub and the composite ring. Hence, radial expansion of the hub does not have to be compatible with radial expansion of the composite ring. Indeed, the hub, which has a lower modulus of elasticity and, further, is purposely designed to expand more rapidly than the composite ring, compresses the plurality of pre-loaded tube assemblies, which absorbs the stress like a spring. The tube assemblies also maintain contact with the radially deforming composite ring. As before, a disadvantage of this hub is that the critical velocity is less than the design operating velocity, which may subject the rotor to potentially deleterious vibrations.

Swett et al. (USP 5,732,603) discloses a flywheel rotor with an expansion-matched, self-balancing, fiber or matrix composite hub, which includes an annular hoop and a pair of compliant diaphragms that are connected by the

hoop. The diaphragms include an annular spring, the compliance of which facilitates maintaining contact at the hub-ring interface. Once again, a disadvantage of this hub is that the critical velocity is less than the design operating velocity, which may subject the rotor to potentially deleterious vibrations.

Swett (USP 6,014,911) discloses a flywheel rotor with a self-expanding hub having a double cone configuration. As the flywheel rotates, the hub surfaces flex, creating compression at the rotor that prevents matrix material of the rotor from pulling apart at high velocities. Here again, a disadvantage of this hub is that the critical velocity is less than the design operating velocity, which may subject the rotor to potentially deleterious vibrations.

Waagepetersen (USP 5,946,979) discloses a flywheel with an expansive, thin-walled, conical or frusto-conical hub, which expansion is made possible by either attaching a flexible, fiber-reinforced plastic material at the end of the hub or adhesively connecting the hub directly to the ring. Here again, a disadvantage of this hub is that the critical velocity is less than the design operating velocity, which may subject the rotor to potentially deleterious vibrations.

Fullwood et al. (PCT WO 97/1313) discloses a conical, fiber-reinforced end cap ("hub") that deflects towards a planar configuration as the rotor speed increases. Such deflection ensures that the rotor and end cap maintain their initial strain. Here again, a disadvantage of this hub is that the critical velocity is less than the design operating velocity, which may subject the rotor to potentially deleterious vibrations.

SUMMARY OF THE INVENTION

Thus, it would be desirable to produce a flywheel hub for attaching a low-density, high-strength, high-growth composite rim to a rotating, high-strength, metal flywheel shaft in such a manner as to substantially maximize the energy storage capacity of the flywheel assembly; to substantially minimize loss of interference fit between the hub and composite rim at very high rotational speeds; and to substantially minimize potentially destructive or deleterious vibrations that may result therefrom.

Therefore, it is an object of the present invention to provide a stiff metal hub for connecting a high-strength metal flywheel shaft to a low-density, high-strength composite rim.

It is a further object of the present invention to provide a stiff metal hub that maintains interference fit with the composite rim at very high rotational velocities, minimizing separation.

It is another object of the present invention to provide a stiff metal hub that substantially minimizes vibrations during high speed operation of the flywheel.

It is a yet another object of the present invention to provide a stiff metal hub that produces a critical speed substantially greater than the design operating speed of the flywheel.

BRIEF DESCRIPTION OF THE DRAWINGS

For a fuller understanding of the nature and desired objects of the present invention, reference is made to the following detailed description taken in conjunction with the accompanying drawing figures wherein like reference character denote corresponding parts throughout the several views and wherein:

FIG. 1 is an illustrative example of a prior art hub from USP 4,860,611;

FIG. 2 is illustrative embodiment of a stiff, metal hub for a rotating energy storage flywheel;

FIG. 3 is an isometric view of an illustrative embodiment of a stiff, metal hub for a rotating energy storage flywheel; and

FIG. 4 is an cut-away isometric view of the illustrative embodiment of a stiff, metal hub for a rotating energy storage flywheel in FIG. 3.

DETAILED DESCRIPTION OF THE INVENTION AND ITS PREFERRED EMBODIMENTS

Flywheel-based energy storage devices 10 comprise relatively simple devices for readily storing and recovering energy. See FIGs. 1 through 3. Conceptually, as a flywheel 10 spins in a vacuum, mechanical kinetic energy is stored, e.g., primarily in the outermost portion (the “rim”) of the flywheel assembly 10. The amount of energy stored in a flywheel assembly 10 is directly proportional to its mass and to the square of the rotational velocity of the flywheel 10. The rotational velocity of the flywheel 10 is largely responsible for the energy storage capacity due to the effect squaring the velocity has on energy storage. Hence, those of skill in the art are developing flywheels 10 that rotate at ever-increasing velocities.

Thus, those of ordinary skill in the art recognize an effective means to increase a flywheel assembly's 10 energy storage capacity is by maximizing rotational inertia by using high-tensile strength, low-density materials, e.g., composite fiber materials at the outermost, composite rim 20, where energy storage potential is greatest. However, use of flexible composite materials in combination with steel or stiff metal alloys is problematic. Indeed, the problem is one of compatibility.

The compatibility problem manifests as the composite rim 20 rotates at higher velocities, wherein centrifugal forces produce hoop and radial stresses that cause the composite rim 20 to “grow” radially. The rotary shaft 25 for all intents and purposes does not deform. Hence, the hub 40 must provide a support platform to the rotating, expanding composite rim 20 and maintain tight interference fit with the non-expanding rotary shaft 25 at all operating speeds. Implicit in supporting the composite rim 30 is a requirement to maintain substantial interference fit between the hub 40 and the rim 20, which is possible only if the hub 40 also grows radially. As a result, the hub 40 features that are most desirable for safe and satisfactory performance of the flywheel assembly 10 include: (i) high material strength to ensure that the hub 40 does not fail; (ii) sufficient flexibility to maintain tight interference fit with the radially-deforming composite rim 20; (iii) sufficient rigidity to maintain tight interference fit with the rigid, non-expansive rotary shaft 25; (iv) sufficient

rigidity to maintain critical speeds well above operating speed; and (v) relatively low material density to substantially minimize stresses due to centrifugal forces.

Indeed, an ideal illustrative embodiment of the present invention comprises a hub 40 that is flexible enough to expand, or deform, radially commensurate with the growth of the composite rim 20 to maintain contact, i.e., tight interference fit, between the rim 20 and the hub 40, and a hub 40 that is rigid enough so that the critical velocity of the flywheel assembly 10 is substantially higher than flywheel 10 design operating speeds, which is to say, that during normal, or habitual, operation, the rotational velocity of the flywheel 10 does not approach the critical velocity of the flywheel assembly 10. As a result, suitable materials for hubs 40 include aluminum, steel, and titanium. From a cost perspective, however, aluminum is preferred over steel or titanium.

Flywheel hubs 40 of the prior art (FIG. 1), however, are typically not flexible enough to maintain tight interference fit between the composite rim 20 and the hub 40 during deformation; and/or are not stiff enough. Indeed, a common shortcoming of the prior art is that the critical velocity of a flywheel assembly 10 is much less than design operating speeds of conventional flywheel assemblies 10, which is to say that prior art flywheels almost universally expose the flywheel assembly 10 to potentially deleterious or damaging vibrations as the frequency of the flywheel rotor passes through its critical frequency before attaining its design operating frequency.

As an example, in FIG. 1 is shown the flywheel assembly 10 of Flanagan et al. (USP 4,860,611) comprising a rigid, metal shaft 25, a unitary, expandable metal hub 40, and composite rim 20, which includes an inner ring 20b and an outer ring 20a. The composite rim 20 of the Flanagan flywheel 10 is shrunk-fit around the expandable hub 40, which is characterized by a plurality of spokes 50 and rim sections 60 between adjacent spokes 50 that purposely have been made thinner to make the rim sections 60 more flexible.

Flanagan et al. addresses the incompatibility problem by pre-shrinking the composite rim 20 onto the hub 40 and, further, by keeping the critical velocity of the flywheel assembly 10 substantially lower than design operating speeds. Hence, at operating speeds less than or equal to critical velocity, the

hub 40 and composite rim 20 maintain tight interference fit because of pre-shrinking. Moreover, at low operating speeds where tight interference fit is maintained, there should be minimal separation of the composite rim 20 from the hub 40, and, therefore, no vibrations near critical velocity to cause resonance. Flanagan et al. further teaches that at higher frequencies, which exceed the critical frequency, the point of resonance has already been passed so there is no further concern of resonance.

By comparison, the metallic hub 40 of the present invention (FIGs. 2, 3, and 4) is appreciably stiffer than the Flanagan hub. The additional stiffness of the metallic hub 40 of the present invention is attributable to the material properties of the hub 40 as well as to its cross-section and dimensions. The hub 40 of the disclosed invention produces a critical velocity and critical frequency that exceed, respectively, the design operating speeds and frequencies of the flywheel assembly 10, which produces a factor of safety against resonance greater than unity. Critical velocity and critical frequency again are defined as the speed and frequency, respectively, at which deleterious resonance occurs.

In a preferred embodiment, critical velocity (or frequency) is between about 1.40 and about 3 times the, respective, design operating speed (or frequency) of the flywheel assembly 10, providing a factor of safety against resonance of between about 40 and 200 percent, respectively. As a result, whereas the Flanagan hub 40 teaches reaching the flywheel assembly's 10 critical velocity at a speed much less than design operating speed, the stiffness of the hub 40 of the present invention produces a critical velocity that is well above design operating speeds.

Hub 40 dimensions and material properties are typically determined interactively using, e.g., finite element analyses and subsequently validated by testing a prototype. For a working embodiment of the present invention, finite element software, e.g., ANSYS produced by Swanson Analytical Systems, is used to size the metallic hub 40 for a desired design operating velocity or frequency.

Indeed, in this illustrative working embodiment, a hub 40 for a design operating speed of about 22,500 revolutions per minute (RPM), which

corresponds to a design operating frequency of 375 Hertz, is desired to provide the required energy storage capability. A factor of safety of, e.g., two (2) necessitates a critical velocity of about 45,000 RPM, which corresponds to a critical frequency of 750 Hertz. In this illustrative example, the hub 40 is made from aluminum. It should be understood, however, that those of ordinary skill in the art may practice the present invention using higher or lower design operating speeds, higher or lower factors of safety, and/or different materials without deviating from the scope and spirit of the present invention.

The hub 40 of the present invention has a central core 70 in tight interference fit with a rigid, rotary shaft 25. The hub 40 is shrunk-fit onto the rigid, rotary shaft 25 by immersing the rotary shaft 25 in liquid nitrogen and heating the central core 70, e.g., in a furnace, to about 250 degrees Fahrenheit. When the supercooled shaft 25 and heated central core 70 have been joined and reach ambient and/or design operating temperatures, there is about an 11 mil interference fit tolerance diametrically.

Dimensions of the central core 70 (length and width) will vary as a function of the design operating speed and frequency of the flywheel 20. At relatively high operating speeds, a portion of the central core 75, which is located directly beneath the web 80, pulls away, or separates, from the rotary shaft 25 creating a holiday, or gap. For that reason, to maintain stability, enough of the central core 70 must remain in tight interference fit with the rotary shaft 25 to arrest any tendency of the rotary shaft 25 to vibrate. In the illustrative, preferred embodiment, for a design operating speed of about 22,500 RPM (375 Hertz), a tight interference fit between the central core 70 and the rotary shaft 25 is maintainable if at least about 1.8 inches of the central core 70 remain in tight interference fit with the rotary shaft 25. Finite element analysis of these design parameters requires a central core 70 thickness of about 1.3 inches and a length of about 6.7 inches.

Extending radially from the central core 70 is a continuous web 80 of approximately uniform thickness. The web 80 flares out near where the web 80 joins the central core 70 and the outer rim 90. The material properties, the thickness, and continuous nature of the web 80 principally provide the stiffness and rigidity to the hub 40. For that reason, the thicker the web 80, the stiffer

the hub 40. Moreover, thicker webs 40 support higher critical velocities. By comparison, the plurality of spokes 50 associated with Flanagan et al. of the prior art is not continuous and less rigid. Consequently, the critical velocity of the prior art is less than the design operating speeds of prior art flywheels 10.

In a preferred embodiment, rotary shafts 25 supported by mechanical bearings (not shown) require a web 80 thickness that produces at least about a 40 percent speed margin, i.e., critical frequency should be about 40 percent greater than design operating frequency. As a result, for a shaft 25 supported by mechanical bearings and a design operating frequency of about 375 Hertz, the critical frequency for design is about 525 Hertz. Finite element analysis of these design parameters requires a web 80 thickness of about 7/8 inch (0.875 in.).

In another embodiment, rotary shafts 25 supported by active magnetic bearings (not shown) require a web 80 thickness that produces at least about a 200 percent speed margin, i.e., critical frequency should be about 200 percent greater than design operating frequency. Hence, for a shaft 25 supported by active magnetic bearings and a design operating frequency of about 375 Hertz, the critical frequency for design is about 750 Hertz. Finite element analysis of these design parameters requires a web 80 thickness of about 2.4 in. It should be noted that those of ordinary skill in the art may practice the present invention on other flywheel assemblies 10 at virtually any design velocity and/or frequency without violating the scope or spirit of this disclosure.

The web 80 is connected to a relatively thin, flange-like outer rim 90. The outer rim 90 is in tight interference fit with the composite rim 20, which has been shrunk-fit to provide the tight interference fit. The composite rim 20 can be fit onto the outer rim 90 in any manner. In an illustrative embodiment, the composite rim 20 is immersed in liquid nitrogen and then placed on the outer rim 90, providing an interference fit with a 35 mil tolerance diametrically.

The dimensions of the outer rim 90 will vary according to the dimensions, design energy storage capacity, and design operating speed of the flywheel 10 as well as the hub's 40 material properties. Thus, variations in these parameters can be made by those skilled in the art without departing from the teachings of this invention.

At very high operating speeds, a portion of the composite rim 95, which is located directly beneath the web 80, pulls away, or separates, from the outer rim 90 creating a holiday, or gap. For that reason, to maintain stability, enough of the outer rim 90 must remain in tight interference fit with the composite rim 20, to minimize vibrations. In one embodiment, a tight interference fit between the outer rim 90 and the composite rim 20 can be maintained if each leg of the flange 90a, 90b is about 5 inches in length, for a total length, including the web 80 thickness, of about 11 inches, when the shaft 25 is operating at a design frequency of about 375 Hertz. However, longer, shorter, and unequal flange leg 90a, 90b lengths are possible with the present invention as long as enough of the outer rim 90 remains in contact with the composite rim 20.

The thickness of the outer rim 90 of the present invention is roughly uniform except in vicinity of the web 80. Indeed, finite element analysis of these design parameters requires an outer rim 90 thickness of about 0.403 inches. The outer rim 90 is substantially longer than the central core 70 because centrifugal forces at the outer rim 90 are greater due to the substantially longer moment arm from the axis of rotation (not shown) to the outer rim 90. Moreover, the coefficient of friction between the steel rotary shaft 25 and the hub 40 is greater than the coefficient of friction between the composite rim 20 and the hub 40. Hence, a longer surface is needed to provide the same amount of frictional resistance at the outer rim 90 as at the central core 70.

A pair of rails 100a and 100b are oriented approximately normal to the surface of the outer rim 90. One rail 100b serves as an axial stop and is directed away from the shaft 25 and towards the composite rim 20. The axial stop rail 100b provides additional protection against the composite rim 20 falling off of the hub 40 during high-speed rotation. Indeed, at very high speeds, the hub 40 and the composite rim 20 grow radially but shrink axially. If the hub 40 shrinks more than the composite rim 20, then, potentially, the composite rim 20 may slide off of the outer rim 90. Positioning an axial stop 100b in the direction of precess provides greater assurance against the composite rim 20 falling off of the outer rim 90 of the hub 40.

The other, balancing rail 100a, which is directed away from the composite rim 20 and towards the shaft 25, is provided to help balance the hub 40. By its design, e.g., dimensions, and/or by applying balancing weights (not shown) thereto, the balancing rail 100a helps to prevent imbalances that could create deleterious vibrations. In another embodiment, an additional balancing (not shown) rail may be added beneath the axial stop 100b. Finite element analysis of these design parameters requires a rail length of about 0.25 in. and a width of about 0.107 in., wherein the width is measured in a direction that is normal to the surface of the outer rim 90.

The composite rim 20 may include any number of coaxial rings 20a, 20b, 20c. The prior art (FIG. 1) shows a bi-annular rim 20 with an inner ring 20b and an outer ring 20a, FIG. 2 shows a tri-annular rim 20 comprising an inner ring 20a, a middle ring 20b, and an outer ring 20c. In a number of different embodiments, the number of rings comprising the composite rim 20 of the present invention ranges from one (1) to five (5). However, there is no reason why more than five rings cannot be used in a composite rim 20.

The hub 40 of the present invention may be fabricated from any high-strength metal or alloy. In a preferred embodiment aluminum is the most economical material for the hub 40. However, steel and titanium also work well.

The following table summarizes results from finite element analyses for an aluminum hub 40 with an assumed design operation speed of 22,500 RPM (375 Hertz):

| | Factor of Safety = 1.4 |
|---------------------------|------------------------|
| Critical Velocity (RPM) | 31,500 |
| Critical Frequency (Hz) | 525 |
| Overall Diameter of Hub | 12.596 in. |
| Length of Outer Rim | 10.920 in. |
| Thickness of Outer Rim | 0.403 in. |
| Web Thickness | 0.875 in. |
| Length of Central Core | 6.700 in. |
| Thickness of Central Core | 1.307 in. |

WHAT IS CLAIMED IS:

1. A stiff, metallic hub for an energy storage device, having a flywheel assembly, wherein the hub produces a critical velocity that exceeds the design operating speed of the flywheel assembly.
2. A stiff, metallic hub as recited in claim 1, comprising:
 - a central core in tight interference fit with a rotary shaft of the flywheel assembly;
 - an outer rim section in tight interference fit with a high-strength, low-density composite fiber rim of the flywheel assembly; and
 - a web section.
3. A stiff, metallic hub as recited in claim 1, wherein the hub is manufactured of material selected from the group comprising aluminum, titanium, and steel.
4. A stiff, metallic hub as recited in claim 2, wherein the web section is continuous.
5. A stiff, metallic hub as recited in claim 1, wherein the critical velocity is between about 1.4 and about 3.0 times the design operating speed of the flywheel assembly.
6. A stiff, metallic hub as recited in claim 2, wherein at high operating speeds, the outer rim section remains flexible enough to deform in a radial direction commensurate with radial deformation of the composite fiber rim of the flywheel assembly to maintain a tight interference fit to substantially minimize vibrations.
7. A stiff, metallic hub as recited in claim 1, wherein the design operating speed of the flywheel assembly is about 22,500 revolutions per minute.

8. A stiff, metallic hub as recited in claim 2, wherein the central core has a critical length to maintain a tight interference fit with the rotary shaft of the flywheel assembly, wherein the critical length is about 1.8 inches at an operating speed of about 22,500 revolutions per minute.

9. A stiff, metallic hub as recited in claim 2, wherein the outer rim section has a critical length to maintain a tight interference fit with the composite fiber rim of the flywheel assembly, wherein the critical length is about 10 inches for an operating speed of about 22,500 revolutions per minute.

10. A stiff, metallic hub as recited in claim 2, wherein the web section has a thickness of about 7/8 inch at an operating speed of about 22,500 revolutions per minute when the rotary shaft is supported by mechanical bearings.

11. A stiff, metallic hub as recited in claim 2, wherein the web section has a thickness of about 2.4 inches at an operating speed of about 22,500 revolutions per minute when the rotary shaft is supported by magnetic bearings.

12. A stiff, metallic hub as recited in claim 2, wherein the outer rim includes at least one balancing rail for balancing the flywheel assembly to substantially minimize vibrations.

13. A stiff, metallic hub as recited in claim 2, wherein the outer rim includes an axial stop to prevent the composite fiber rim from falling off of the outer rim of the hub during high speed operation.

ABSTRACT OF THE DISCLOSURE

Several embodiments of a stiff, metallic hub for an energy storage devices are disclosed in the present invention. The stiff hub produces a critical velocity that is significantly greater than the design operating speed of the flywheel assembly so that resonant frequency is never reached during normal operation of the energy storage device's flywheel assembly. The stiff hub comprises a central core section that maintains a tight interference fit with the rotating shaft; an outer rim section that maintains a tight interference with the high-strength, low-density composite fiber rim, in which energy primarily is stored; and a web section that is situated therebetween, extending radially from the rotary shaft. At high operating speeds, the outer rim of the hub expands radially commensurate with expansion of the composite fiber rim so that enough of the outer rim remains in tight interference fit with the composite fiber rim to substantially minimize vibrations.

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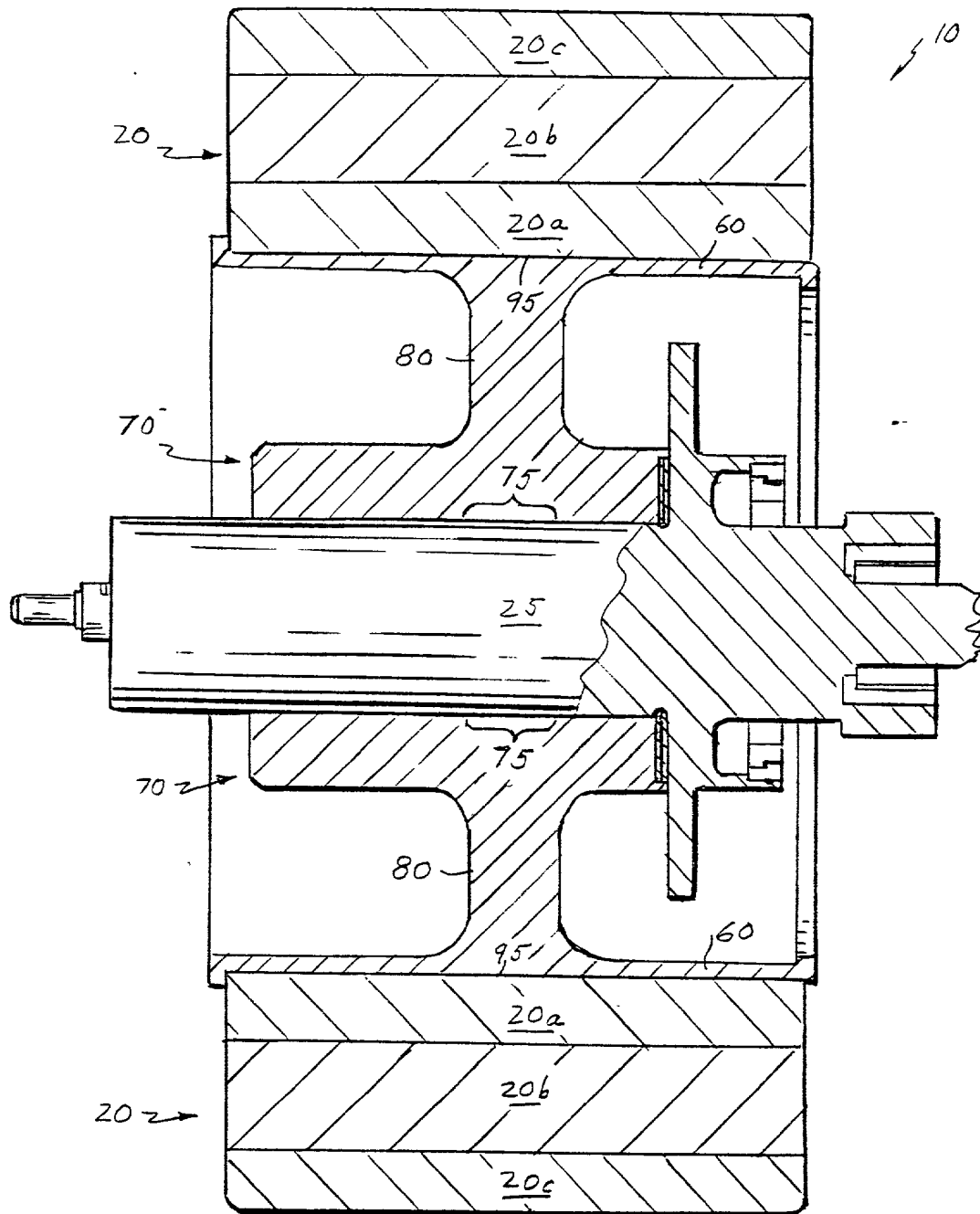


FIG. 2

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DECLARATION AND POWER OF ATTORNEY

As a below named inventor, I hereby declare that: My residence, post office address and citizenship are as stated below next to my name. I believe I am the original, first and sole inventor (if only one name is listed at 201) below or an original, first and joint inventor (if plural names are listed at 201-208 below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:

STIFF METAL HUB FOR AN ENERGY STORAGE ROTOR

which is described and claimed in:

- ☒ the specification attached hereto.
- ☐ the specification in U.S. Application Serial Number _____, filed on _____.
- ☐ the specification in PCT international application Number, filed on _____; and was amended on _____.

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above. I acknowledge the duty to disclose information which is material to the examination of this application in accordance with Title 37, Code of Federal Regulations, §1.56(a). I hereby claim foreign priority benefits under Title 35, United States Code, §119 of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed.

| Prior Foreign/PCT Applications and Any Priority Claims Under 35 U.S.C. §119: | | | |
|--|-------------|---------|--|
| Application No. | Filing Date | Country | Priority Claimed Under 35 U.S.C. §119 |
| | | | <input type="checkbox"/> YES <input type="checkbox"/> NO |
| | | | <input type="checkbox"/> YES <input type="checkbox"/> NO |

POWER OF ATTORNEY: As a named inventor, I hereby appoint the following attorney(s) with full powers of association, substitution and revocation to prosecute this application and transact all business in the Patent and Trademark Office connected therewith.

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I hereby further declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further, that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

| | |
|---|----------------------------------|
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